SEMICONDUCTORS EXPLAINED

An Intuitive Introduction to Foundations with Mathematics

SREEDATTA KARTHIKEYA GORTHI

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Introduction

Modern technology often feels like magic. A small chip can recognize your voice, control a robot, or process millions of decisions every second. But behind this magic lies a surprisingly simple idea: **logic**, built from **semiconductors**, guided by **mathematics**.

This booklet is written to remove the mystery.

You do not need to be an expert, and you do not need to memorize complex formulas to begin. Instead, we will build understanding the same way engineers and scientists do—**from intuition first**, then **from structure**, and only then **from mathematics**. Every equation you see will exist for one reason only: to make an idea clearer, not harder.

At the heart of digital electronics is a very small question:

Can something be on or off?

From this simple choice, we build logic gates. From logic gates, we build circuits. From circuits, we build systems. And from systems, we build devices that shape the modern world.

Semiconductors are the physical materials that make this possible. They sit between conductors and insulators, allowing us to control the flow of electrical charge with precision. When shaped carefully, they become transistors—tiny electronic switches that can make decisions faster than any human ever could.

An **FPGA** (Field-Programmable Gate Array) is a special kind of chip that lets us *rearrange* these decisions. Instead of being locked into one behavior, an FPGA can be reconfigured to become many different digital circuits. Today it might be a calculator. Tomorrow, a signal processor. Next week, the brain of a robot.

To understand FPGAs, we must understand three foundations:

- **Logic** — how true and false, yes and no, become computation
- **Semiconductors** — how physical materials carry and control electrical behavior
- **Mathematics** — how patterns, relationships, and certainty are described precisely

Mathematics will appear throughout this booklet, but gently. Boolean algebra will explain logic. Simple equations will describe voltage, current, and timing. Graphs and symbols will be used as a *visual language*, not as obstacles.

Think of math here as a *map*, not a test.

By the end of this booklet, you should not only know **how** digital systems work, but **why** they are designed the way they are. You will begin to see logic in hardware, hardware in equations, and equations as clear statements about reality.

Most importantly, you will gain the confidence to look at a digital circuit or an FPGA design and say:

This makes sense.

That is the real goal of this journey.

We assume that there is some basic understanding of some physics principles such as Newtonian mechanics before we get started. However, I will briefly try to explain some of the necessary concepts to brush up. When we push or pull at something, we often say that we are exerting a "force". What can we think of force as? We need a greater force to push something heavier- so force needs to be related in such a way to the mass of an object so that an increase in mass increases force as well. But force cannot be equal to mass! So some more relation is needed. Now you want to change the motion of a heavy elephant - you would probably say you would need a gigantic force - but why? You will need to change the elephant's momentum which keeps it going- so there's something related to slowing/speeding up or"accelerating or decelerating". Thus, we get the famous Newtonian equation, Force = Mass x Acceleration. Sir Isaac Newton's laws play a pivotal role in understanding classical physics, which lay foundations for understanding semiconductors at the deeper, mathematical level. The first law of Newton states that an object at rest stays at rest and an object in motion stays in motion unless acted on by an external unbalanced force. The third law states that when an object exerts a force on another object, the other object exerts a force equal to the initial force on the first object. When we think of work, we often think of the effort put in doing something,. But here is the nuance. You're doing work when you push the object, but so, can work=force? Certainly not. When you do a work to benchmark-level, you are appreciated, otherwise, if you do negligible work or effort, it doesn't much garner attention. Similarly, moving an object to some distance accounts for work, while pushing the wall with a 'small' force doesn't do any good work. Thus, we define work as the energy transferred when you move it- or quantitatively, Work = Force x Displacement. Similarly, we will explore relations between these and electrical physics - which will finally help us to make the route to VLSI design even easier.

PART I — Foundations

1 Potential and Kinetic Energy - The Beginnings

Energy is the silent architect behind every phenomenon we observe — the hidden thread that connects the falling of an apple, the turning of a turbine, and the heartbeat of a living cell. In physics, energy is not merely a vague notion of "power" or "strength"; it is precisely defined as the *capacity to do work*.

Work itself, though it sounds everyday, carries a sharply mathematical identity. When a force $\vec{F}$ acts on a body and causes a displacement $\vec{s}$, the work done is the scalar product of the two:

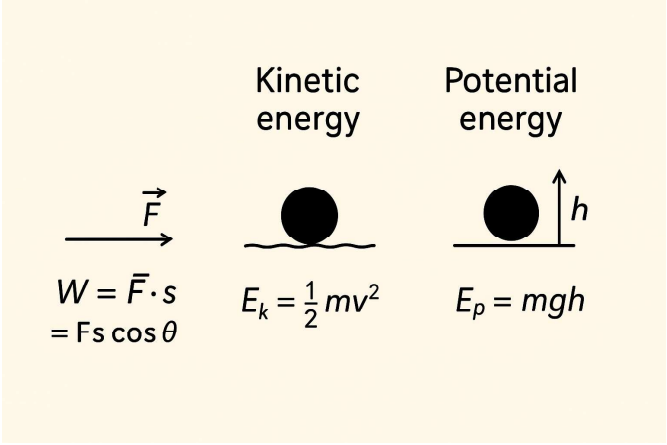

Figure 2: Work, Kinetic and Potential Energy

$$W = \vec{F} \cdot \vec{s} = Fs\cos\theta$$

where θ is the angle between the directions of force and displacement. The units of work and energy are the same — the joule (J) — because energy is essentially the stored potential for doing work.

Energy comes in many guises, but the most intuitive and classical forms are *kinetic* and *potential* energy. Kinetic energy is the energy of motion; potential energy is the energy of position or configuration. These two are the twin currencies of the mechanical world.

Imagine a dam. The water resting behind it, held high, possesses gravitational potential energy due to its elevation. The moment it is released, that stillness converts into motion — potential energy cascading into kinetic energy. The relationship is beautifully symmetric:

$$E_p = mgh \qquad \text{and} \qquad E_k = \frac{1}{2}mv^2$$

Example Illustration

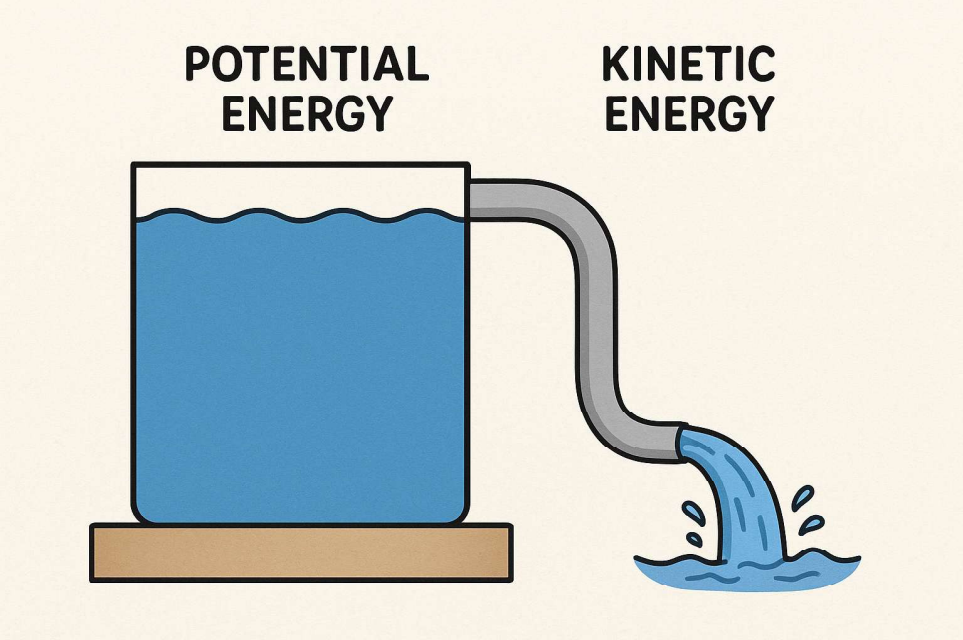

Figure 3: Analogy of water flowing from a tank representing potential and kinetic energy.

As the water falls, h decreases while v increases, but the sum $E_p + E_k$ remains nearly constant, neglecting losses due to friction or turbulence. That simple conservation — energy transforming but never vanishing — is the central heartbeat of physics.

This transformation is not confined to water or motion alone. The same rhythm plays out in electricity, heat, and even biological systems. In an electrical circuit, voltage behaves like height — it represents *potential energy per unit charge* — while current corresponds to the rate of flow, or kinetic expression, of that energy. Their product,

$$P = V \times I$$

is power — the rate at which energy flows through the system.

In thermodynamics, a similar parallel emerges. The internal vibrations and configurations of molecules represent stored (potential) energy; when temperature rises, this stored energy becomes agitation — molecular kinetic energy. Every act of heating, flowing, or radiating follows this constant dance of conversion, never breaking the rule that energy merely changes form, never essence. In reality, a portion of energy in both systems — the waterfall and the electric current — inevitably converts into heat, reminding us that while energy is conserved, not all of it remains useful.

If one returns to the dam analogy, the connection becomes visual. The height of the tank represents potential, while the water jetting out represents kinetic. When the tank is sealed, energy is poised, silent, waiting. Open the gate, and energy becomes motion, sound, and spray — a pure display of kinetic freedom. The same is true of a compressed spring, a charged capacitor, or a stretched bow: each holds potential that can at any moment unfurl into movement.

Thus, every physical process — from a river carving a valley to a neuron firing an impulse — is a story of transformation between stored and moving energy. The total remains constant, a quiet assurance that the universe, though restless, never wastes a single joule.

2 Introduction to Current and Voltage - With Electronics

From the small jolt of a doorknob spark to the blinding flash of lightning that splits the sky, electricity surrounds us in both subtle and spectacular forms. It powers our homes, fuels industries, and drives the modern world. Yet behind this invisible force lies one of nature's most fundamental ideas — the **electric charge**, a property so deeply woven into the fabric of matter that it defines how the universe behaves at its most basic level. At the heart of it all is the **atom** — a tiny, wondrous structure that has fascinated scientists and philosophers for centuries. The concept of the atom dates back to ancient times, when the Indian philosopher **Kannada** wrote of indivisible particles in his *Vaisheshika Sutras*, and the Greek thinker **Democritus** envisioned matter as composed of tiny, uncuttable units. Centuries later, this ancient idea blossomed into a cornerstone of modern science. The late 19th and early 20th centuries were a golden age of discovery. **J.J. Thomson** uncovered the electron and proposed the "plum pudding" model of the atom; **Ernest Rutherford** revealed the dense nucleus through his gold foil experiment; and **Niels Bohr** refined this picture by showing that electrons orbit the nucleus in specific energy levels. Then came **Erwin Schrödinger**, whose quantum model replaced neat orbits with the elegant blur of probability clouds, and **James Chadwick**, who discovered the neutron — a particle so shy of charge that its existence remained hidden for years. Each breakthrough reshaped our understanding of matter, energy, and the universe itself.

Even today, that journey continues. Scientists have uncovered **bosons**, **fermions**, **positrons**, and even **antimatter**, expanding our grasp of the subatomic world. It's a poetic irony — we, who are made of atoms, are endlessly striving to understand atoms.

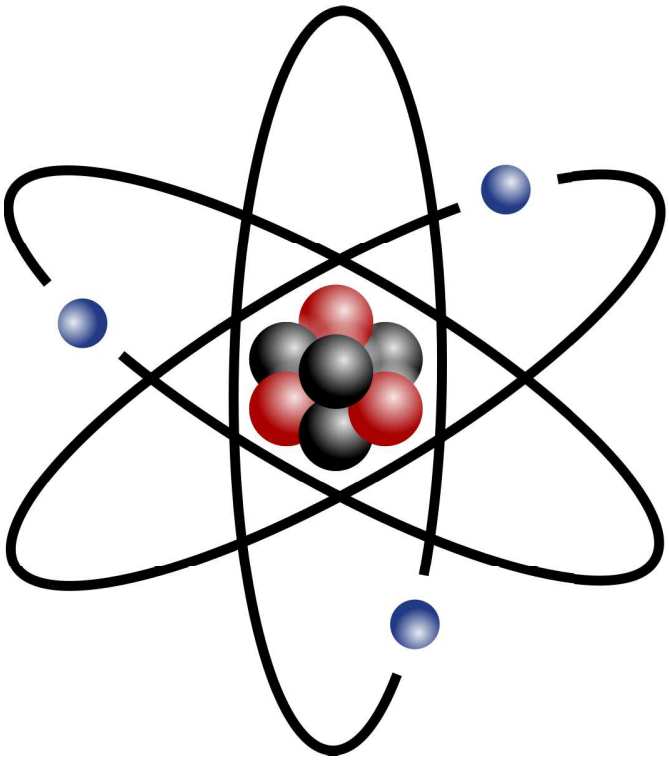

Figure 4: Stylized Atom Diagram - Wikimedia

But when it comes to **electricity**, two of these particles take center stage: the **electron**, with its negative charge, and the **proton**, with its positive one. The interplay between them creates the forces that drive every electric phenomenon we know.

When an atom **loses** or **gains** electrons, it becomes an **ion**. Losing electrons makes it positively charged — a **cation** — while gaining them makes it negatively charged — an **anion**. This

exchange of charge, simple yet profound, forms the basis of countless natural and technological processes: from the chemistry of life inside our cells to the current running through a circuit.

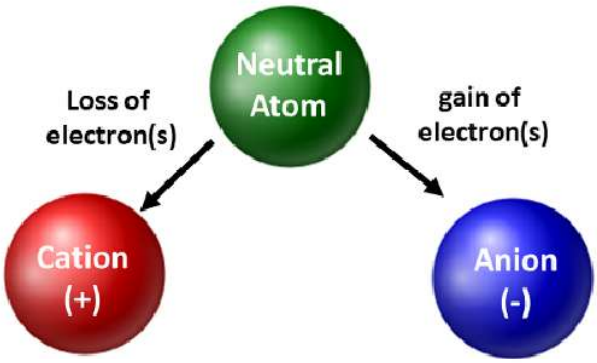

Figure 5: Ions - Chemistry LibreTexts

Electric charge, at its core, is a kind of invisible glue — attracting, repelling, and shaping the structure of everything that exists. When these charges move together in a coordinated flow through a conductor, they create an **electric current** — the lifeblood of every electrical system. Imagine it like water flowing through a riverbed: the electrons are the water molecules, and the wire is the river channel guiding their path.

What causes them to move is **voltage** — the electric "pressure" or **potential energy** that pushes the charges along. It's much like water stored in a tank at a height; the greater the height difference, the stronger the flow when it's released. In this sense, voltage is the **potential energy**, and current is the **kinetic energy** — the motion that results when potential becomes action. Resistance comes into play in our systems - restricting flows like electrical friction.

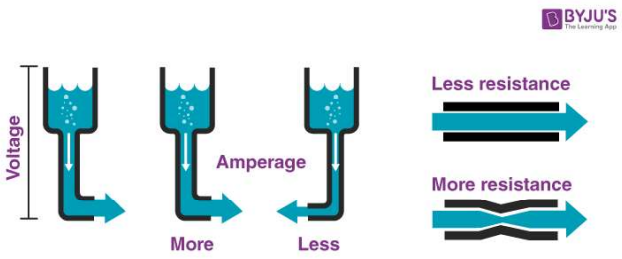

Figure 6: Voltage, Current and Resistance - BYJU'S

Together, they form a delicate balance, a dance between stillness and movement, between potential and flow. From that dance arises everything — the hum of a machine, the glow of a lightbulb, the spark of life itself. Electricity, born from the ancient atom, continues to pulse through the veins of our civilization, a timeless current connecting the mysteries of matter with the marvels of human invention.

Voltage, current, and resistance are connected by this equation, called Ohm's Law, named for physicist George Ohm.

$$V = I \times R$$

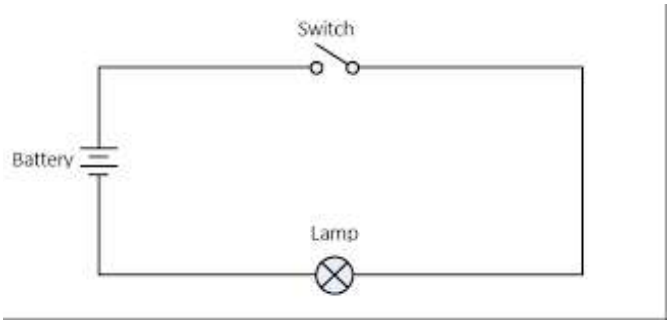

Figure 7: Simple Circuit - ResearchGate

Electrical Work and Power: The Flow of Energy

However, the story of electricity is even more nuanced than that. Earlier, when we discussed energy, we encountered the ideas of **work** and **power** — two fundamental quantities that describe how energy is transferred and used. Naturally, electricity has its own equivalents of these mechanical concepts.

When electric charge moves through a circuit, **energy is transferred** — this is the electrical work being done. It is the same energy that makes a lightbulb glow, a heater warm, or a motor spin. In simple terms, **electrical work** is the total energy transferred to move charge through an electric potential difference.

Electrical Work

- **Definition:** The total energy transferred when an electric charge moves through a potential difference.
- **Formula:**

$$W = V \times Q$$

  where:

  - W is the work done (or electrical energy transferred),
  - V is the voltage (potential difference), and
  - Q is the electric charge.

- **SI Unit:** The joule (J).

The same unit, the joule, is used for mechanical energy, highlighting that all forms of energy are connected at a fundamental level.

Electrical Power

Just as power in mechanics represents the **rate at which work is done**, electrical power measures **how quickly electrical energy is converted** into other forms such as light, heat, or motion. It can be expressed using calculus, but for simplicity in uniform cases-

- **Definition:** The rate of doing electrical work or transferring electrical energy per unit time.
- **Formula:**

$$P = \frac{W}{t}$$

  where:

Figure 8: Electrical Work and Power

- P is the power,
- W is the work done, and
- t is the time taken.

By substituting $W = VQ$ and using the definition of electric current $I = \frac{Q}{t}$, we get the familiar and practical expression:

$$P = V \times I$$

This equation shows that power in an electrical circuit depends on both the **voltage** (the driving push) and the **current** (the flow of charge).

Using Ohm's Law ($V = I \times R$), we can also express power in two alternative forms:

$$P = I^2R \quad \text{and} \quad P = \frac{V^2}{R}$$

Each form reveals a different relationship among the quantities involved — how power depends on current, voltage, or resistance in a circuit.

- **SI Unit:** The watt (W), where

$$1 \text{ Watt} = 1 \text{ Joule per second.}$$

A Physical Analogy

If we imagine an electrical system as a flowing river, then:

- **Voltage** is the pressure that drives the flow,
- **Current** is the volume of water moving through the river,
- and **Power** is the rate at which energy is carried by that flow.

Figure 9: Energy Transformation - (Image Credits-Gemini, Google

The higher the pressure (voltage) and the stronger the flow (current), the greater the power delivered — just as a fast, forceful river turns a mill more efficiently than a gentle stream.

Electricity, therefore, is not merely about particles and forces. It is about the continuous **conversion of potential into motion**, of stored energy into flow. From the tiniest atom to the machines that shape our world, this same elegant transformation of energy unfolds — endlessly dynamic, endlessly vital.

3 The Reason and Philosophy - The Transformation of Energy

Transformation of energy from one form to another forms the cornerstone of modern living. From photovoltaic cells that convert sunlight into electricity to the natural metabolic processes that sustain life, the constant movement and conversion of energy underpin every aspect of existence. The way in which we use energy may vary across systems and technologies, yet the fundamental truth remains unchanged: energy itself is constant, merely shifting in form and function. This principle not only defines the physical laws governing the universe but also reveals a deeper philosophical understanding of continuity and transformation.

From a scientific perspective, the transformation of energy is rooted in the **First Law of Thermodynamics**, which states that energy can neither be created nor destroyed, only transformed from one form to another. This fundamental rule explains why every natural and technological process involves an exchange of energy. In solar panels, radiant energy from the sun becomes electrical energy. In plants, the process of photosynthesis converts solar energy into chemical energy. Similarly, in the human body, chemical energy derived from food transforms into kinetic energy, enabling movement and thought. Without such transformations, energy would remain static and purposeless, incapable of producing the dynamic interactions that sustain life and matter. Thus, energy transformation is not only a scientific necessity but also the mechanism through which the universe maintains its perpetual motion and balance.

Beyond its scientific dimension, the transformation of energy carries profound **philosophical implications**. It symbolizes the continuity of existence — the idea that nothing truly disappears but only changes its form. This concept echoes through both Eastern and Western thought. Through this lens, energy becomes a metaphor for life itself: dynamic, interconnected, and eternal. The same sunlight that nourishes a tree may one day warm human hands by a

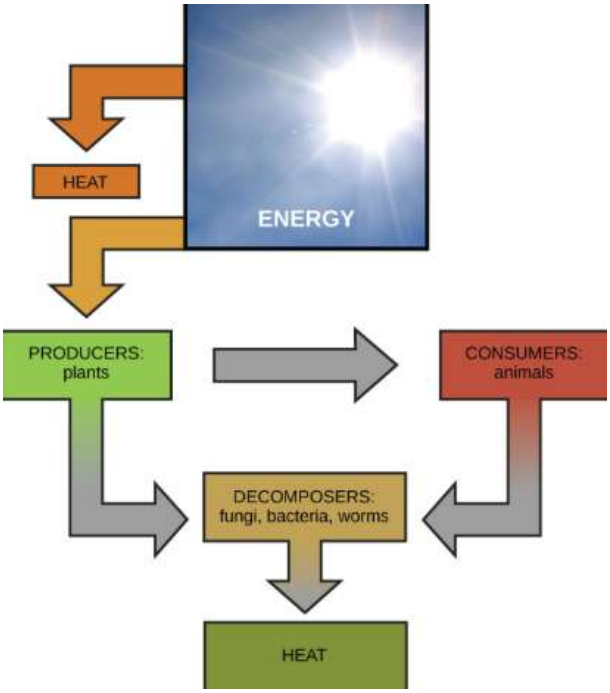

Figure 10: Energy Transformation- umn.edu

fire, demonstrating the seamless continuity of energy across time and space.

In the modern era, humanity's ability to harness and transform energy defines the trajectory of civilization. From the combustion engines of the industrial age to the renewable technologies of today, each advancement reflects our growing mastery of energy conversion. Yet, this mastery also carries ethical and environmental responsibilities. The challenge of our time lies not merely in transforming energy but in doing so **efficiently and sustainably**, minimizing waste and preserving ecological harmony. The pursuit of cleaner energy transformation thus represents both a scientific endeavor and a moral imperative — a means of aligning technological progress with the enduring rhythms of nature. In this unity of physics and technology, the transformation of energy is not merely a process — it is a promise: that every spark of understanding can power a more sustainable and enlightened world

In essence, the transformation of energy is far more than a physical process; it is a **philosophy of continuity and renewal**. It reminds us that all forms of life and matter are interconnected through the same eternal flow of energy — ever-changing, yet never lost. Through understanding and respecting this universal cycle, humanity not only advances technologically but also deepens its appreciation of the intricate balance that sustains all existence.

4 Curiosity, Conclusions and Connections - From Foundations to Fascinations

So far, we have explored the fundamental concepts of energy — kinetic and potential — and their roles as the building blocks of physical processes. From these classical notions arise the basic principles used in modern electronics: electrical voltage, power, and current. Just as mechanical energy manifests through motion and position, electrical energy flows through potential difference and resistance, giving rise to the intricate behavior of electronic systems. This understanding forms the foundation upon which all modern technology stands, bridging the gap between the laws of physics and the design of complex computational architectures.

At the core of these architectures lies the semiconductor — the material heart of the modern

Figure 11: Sustainable Energy Management

world. Semiconductors form the basis of **Very-Large-Scale Integration (VLSI)**, a discipline where millions, or even billions, of transistors are fabricated onto a single chip. Each transistor operates on the same principles of energy transformation, converting electrical potential into logical operations. They, at heart, are governed by these physics concepts. Through carefully engineered doping and layering processes, semiconductors control the flow of electrons, enabling the design of processors, memory systems, and embedded circuits that power every aspect of contemporary life.

Building upon these foundations, systems such as **RISC-V** and **Field-Programmable Gate Arrays (FPGAs)** exemplify the next evolution of this continuum. RISC-V, with its open-source instruction set architecture, represents a shift toward accessibility, adaptability, and efficiency — principles that parallel the sustainability ethos in energy systems. FPGAs, on the other hand, embody flexibility and reconfigurability, allowing hardware to be repurposed dynamically, reducing waste and extending device lifecycles. In both cases, innovation in electronic design mirrors the broader quest for efficiency in the use and transformation of energy itself.

As technology advances, the parallel between **electronic efficiency** and **energy sustainability** becomes increasingly apparent. Every computation, every signal transmission, and every data process draws upon energy, and as our dependence on digital infrastructure grows, so does our responsibility to use that energy wisely. The design of low-power VLSI circuits, energy-aware algorithms, and renewable-energy-driven computing infrastructures are no longer optional pursuits — they are moral and environmental imperatives. Just as we have learned to harness energy from nature without depleting it, we must learn to compute with the same consciousness: maximizing output while minimizing waste.

Ultimately, the transformation of energy — from sunlight to electricity, from electrons to information — reflects a continuous thread that connects the physical, the technological, and the philosophical. Whether in the flow of current through a semiconductor or the flow of ideas through human intellect, transformation remains the essence of progress. In embracing both innovation and sustainability, humanity stands not only as a consumer of energy but also as a steward of its perpetual flow. The future of technology, like the universe itself, will depend on our ability to transform energy responsibly — with intelligence, balance, and respect for the continuum that sustains all existence.

PART II — Circuits

1 Energy Flow- Soft or Quick?

Let us consider a simple example, using familiar principles from basic physics. When a balloon is inflated and tied, it stores potential energy in the form of pressurized air. If the balloon is then punctured, the stored energy is released spontaneously and uncontrollably. The air rushes out almost instantaneously, producing sound waves and dispersing the energy irreversibly. Once released in this manner, the energy cannot be captured or reused.

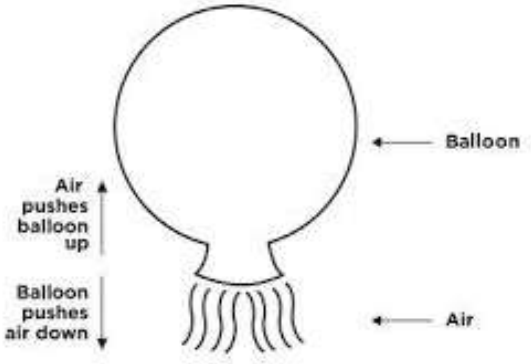

Figure 2: Ballon Untied - Science World

In contrast, if the balloon's opening is simply untied, the pressurized air is still released, but in a controlled way. The potential energy stored in the compressed air is gradually converted into kinetic energy of the escaping air jet, which can perform useful work—for example, propelling the balloon forward. The energy transformation is directed and usable, rather than lost in a sudden, dissipative event. An analogous situation occurs in a battery.

A charged battery stores chemical potential energy. If the battery is short-circuited, this energy is released rapidly and irreversibly as heat, light, or other dissipative effects, much like a punctured balloon: the energy becomes unavailable for performing controlled work. However, when the battery is connected to a proper electrical circuit, the chemical potential energy is converted in a regulated manner into electrical energy, which then drives currents to perform useful and recoverable work—analogous to the controlled release of air from an untied balloon.

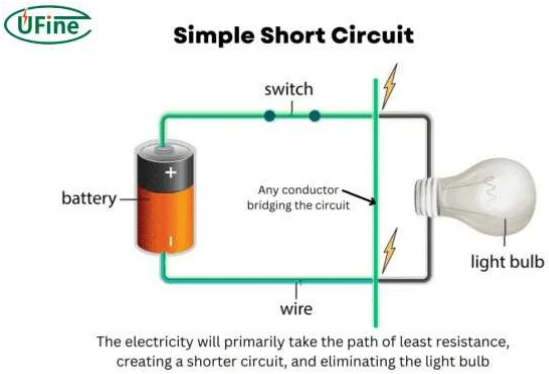
UFine
Simple Short Circuit
switch
battery
Any conductor bridging the circuit
light bulb
wire
The electricity will primarily take the path of least resistance, creating a shorter circuit, and eliminating the light bulb

Figure 3: Battery Short Circuit - Ufine

In both cases, the distinction is between spontaneous, uncontrolled dissipation of stored energy and controlled, directed transformation of that energy into work. But this is not limited to mechanical or electrical systems alone, but also in thermodynamic systems. Imagine

we have a sealed container filled with an ideal gas, and we want to expand its volume from 2.0 liters to 5.0 liters while keeping the temperature constant at 300 K. There are two very different ways to make this happen. In the first scenario, the gas is confined in a cylinder

with a movable piston. We begin with the gas at 2.0 liters and 300 K. To expand it, we gently heat the gas using an electric heater, allowing it to push the piston outward. This process is slow and carefully controlled, ensuring the temperature remains constant throughout — a textbook example of an *isothermal expansion*. As the gas expands to 5.0 liters, it absorbs a specific amount of heat from the heater. Because the expansion is gradual and the gas does work by pushing the piston, energy is transferred into the system as heat. Now consider a second, more dramatic approach. This time, the gas is placed in the lower

half of a rigid, thermally insulated container, separated from an empty upper half by a thin, breakable partition. The lower compartment holds 2.0 liters of gas at 300 K, just like before. But instead of heating it, we simply break the partition. Instantly, the gas rushes into the upper compartment, expanding to fill the full 5.0 liters. No heat is added — the container is insulated — and the gas does no work, since it isn't pushing against anything. This sudden, uncontrolled expansion into a vacuum is known as a *free expansion*. What's fascinating

is that despite the wildly different processes, the gas ends up in the same final state: 5.0 liters at 300 K. Experiments confirm that for an ideal gas, free expansion doesn't change the temperature. But the paths taken to reach that final state couldn't be more different. In the first case, heat is added and work is done. In the second, neither occurs. This highlights a key principle in thermodynamics: while state variables like temperature and volume depend only on the initial and final conditions, quantities like heat and work depend on the *path* taken between those states.

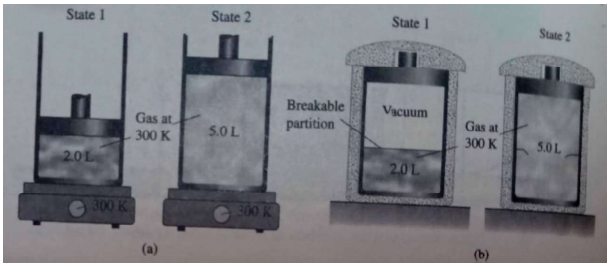

Figure 4: Expansion

2 Ohm's Law

Ohm's Law is one of the most fundamental principles in the study of electricity, discovered by the German physicist Georg Simon Ohm in 1827. Through a series of meticulous experiments, Ohm observed that the electric current flowing through a conductor is directly proportional to the voltage applied across it and inversely proportional to the resistance of the conductor. This relationship is elegantly captured in the formula:

$$V = I \cdot R$$

where V stands for voltage, I for current, and R for resistance. Essentially, this means that if you increase the voltage in a circuit while keeping the resistance constant, the current will increase proportionally. Conversely, if the resistance increases while the voltage remains the same, the current will decrease. This simple yet powerful law laid the groundwork for modern electrical engineering and circuit design.

Figure 5: George Simon Ohm - MagLabs

To understand Ohm's Law intuitively, imagine water flowing through a pipe. The voltage is like the water pressure pushing the flow, the current is the amount of water moving through the pipe, and the resistance is the pipe's width or any obstruction that slows the flow. A wider pipe (lower resistance) allows more water (current) to flow for the same pressure (voltage), while a narrower pipe (higher resistance) restricts the flow. This analogy helps visualize how voltage, current, and resistance interact in an electrical circuit. Ohm's Law is used extensively in designing electrical systems, calculating power consumption, and troubleshooting faults. For example, if a device operates at 10 volts and has a resistance of 5 ohms, the current flowing through it can be calculated as:

$$I = \frac{V}{R} = \frac{10}{5} = 2 \text{ amperes}$$

However, Ohm's Law has its limitations. It applies only to materials known as *ohmic conductors*, which have a constant resistance regardless of the voltage or current. Many modern electronic components, such as diodes and transistors, do not follow this linear relationship. Their resistance can vary depending on factors like temperature, voltage, or even light exposure. Despite these exceptions, Ohm's Law remains a cornerstone of electrical theory and practice. It provides a clear and reliable framework for understanding how electricity behaves in most everyday situations, from powering household appliances to designing complex electronic circuits. Its enduring relevance is a testament to the clarity and utility of Ohm's original insight into the nature of electric current.

3 Switches

Using energy judicously is pivotal in its management. Utlizing it just in different ways doesn't mean we can waste it. In modern applications, a brilliant invention from intellectual ferment of John Holmes, is a switch, transforming how we look at the world every-day. Formally, a switch is defined as anything which can make or break a circuit, it can obstrcut or allow it to pass. They are different types of switches such as push switches,slide switches, DIP switches, diode-based switches, etc.. with each in a unique way. Lets breifly take a look at each of their type.

Figure 6: Push Switch - Project Point

Push switches are a type of temporary controllers where the stop the flow of current till where is physicacally actuated.

Figure 7: Slide Switch - Element 14

Slide switches are mechanical electrical components that use a sliding motion to control current flow in a circuit, commonly used for on/off functions and mode selection in various electronics. They are available in different configurations and sizes for various applications.

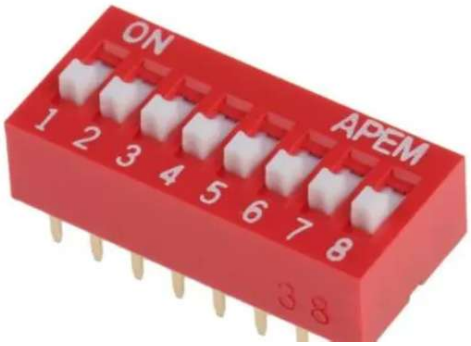

Figure 8: DIP Switch - RS Components

A DIP switch (dual in-line package switch) is a manual electric switch with multiple tiny switches grouped together in a single unit designed to be mounted on a printed circuit board (PCB). They are used to customize the behavior or configuration settings of an electronic device at the hardware level without the need for software.

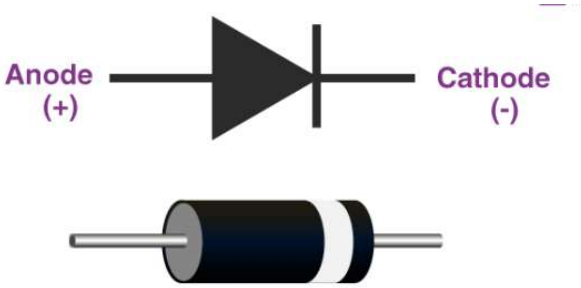

Figure 9: Diodes - BYJU'S

Diodes are the heart to every electronic appliance. diodes A diode is a two-terminal electronic component that acts as a one-way valve for electric current, allowing it to flow in one direction (forward bias) while largely blocking it in the reverse direction. This unique characteristic makes diodes essential for various electronic applications. Key Functions and

Applications The primary function of a diode is to control the direction of current flow. This property is utilized in numerous ways: Rectification: This is the most common application, where diodes convert alternating current (AC) into pulsating direct current (DC). This is a crucial step in the power supplies of nearly all electronic devices, such as phone chargers and computer power adapters. Voltage Regulation and Protection: Zener diodes are specifically designed to maintain a constant voltage across their terminals, even as the current or input voltage changes. This property is used to protect sensitive components from overvoltage or voltage spikes in a circuit. Signal Processing: Diodes are used in circuits for signal modulation, demodulation (such as in AM radio receivers to extract the audio signal), clipping, and clamping to modify or limit signal waveforms. Logic Gates: Diodes can be combined with resistors to implement basic logic functions (like AND/OR gates), which are fundamental building blocks of digital electronics. Optical Applications: Specialized diodes convert electrical energy into light (Light Emitting Diodes or LEDs, and laser diodes) or convert light into electrical current (photodiodes, solar cells). Common Types of Diodes Different types of diodes are tailored for specific functions: Standard Silicon Diodes (P-N Junction Diodes): The general-purpose diodes used in most basic rectification and switching applications. They have a forward voltage drop of about 0.7 volts. Light Emitting Diodes (LEDs): Emit light when current flows through them in the forward direction. They are widely used in modern lighting, displays, and indicators due to their energy efficiency and long life. Zener Diodes: Designed to operate reliably in the reverse breakdown region, allowing them to provide a stable reference voltage, making them ideal for voltage regulation circuits. Schottky Diodes: Characterized by a metal-semiconductor junction, they have a lower forward voltage drop (typically 0.2 to 0.3 volts) and faster switching speeds compared to standard P-N junction diodes, making them suitable for high-frequency applications. Photodiodes: Operate in reverse bias and produce an electrical current when exposed to light. They are used in light sensors, solar cells, and fiber optic communication systems. Laser Diodes: Similar to LEDs but produce a focused, coherent beam of light. They are commonly used in CD/DVD drives, laser pointers, and optical telecommunications.

Figure 10: LEDs- Wikipedia

An LED, or Light Emitting Diode, is a fascinating blend of two fundamental electronic concepts: the diode and the switch. At its core, an LED behaves like a diode—it allows electric current to flow in only one direction. This unidirectional behavior is crucial because it ensures that the LED lights up only when the current flows the right way, known as forward bias. If you try to push current in the opposite direction, the LED blocks it, just like any standard diode would. But what makes LEDs special is that when this forward current flows, the semiconductor material inside the LED releases energy in the form of light. That's the "light-emitting" part of the name.

Now, think of a switch as a simple control mechanism—something that toggles between allowing and stopping current. While an LED isn't a switch itself, it often acts as a visual companion to one. For example, when a switch is turned on in a circuit, it allows current to flow, and the LED lights up to signal that the circuit is active. In this way, LEDs serve

as intuitive indicators of switching states. They're used in everything from power buttons to status lights, giving immediate feedback about whether a device or system is on, off, or in transition.

So, in narrative terms, imagine a one-way street (the diode) with a traffic light (the LED) at the entrance. The switch is the gate that opens or closes access to the street. When the gate opens and traffic flows in the correct direction, the light turns on, signaling movement. If the gate is closed or traffic tries to go the wrong way, the light stays off. This interplay of directionality, control, and illumination makes LEDs not just functional components, but storytellers in the language of electronics—revealing the invisible dance of current with a simple glow.

Mutiple Switches are a combination of two o more switches used a operate a circuit. We see examples like a two-way switch at our houses.

(Expanded) Understanding Multiple Switches

Multiple switches are not just convenient—they demonstrate a deeper principle of electrical control: distributed authority over the same circuit. In a two-way (staircase) lighting system, two switches control the same lamp from different locations. Each switch flips the state of the circuit path, meaning the lamp can turn ON or OFF depending on the *combination* of switch positions.

This introduces students to the idea of logic networks: - Two switches in series behave like a logical AND. - Two switches in parallel behave like a logical OR.

Thus, the humble household light switch silently teaches Boolean algebra. This is the same logic that later scales into computer architecture and CPU design—millions of such switching elements cooperating to perform computation.

Multiple switches therefore serve as a bridge between: - everyday electrical wiring, and - the binary, logic-driven world of digital electronics.

—

4 Curiosity, Conclusions and Connections - From Foundations to Fascinations

So far, we have explored the fundamental concepts of electricity and diodes- and switches in quite a detail. These lay foundations for modern electronic appliances we deal with every day - such as PCB boards too.

Curiosity is the spark that binds all these ideas together. When you ask *why* a battery heats during a short circuit, or *how* a diode "decides" which direction to allow current, you begin connecting physical intuition with engineering design. Every switch flipped, every LED lit, and every circuit simulated in Wokwi reveals a tiny piece of the vast network of principles underlying modern electronics.

These small experiments are not isolated tasks—they are stepping stones toward understanding how large, complex systems such as processors, RAM modules, and even entire computers function. The same Ohm's Law that governs a single resistor also governs power distribution networks inside microchips. The same logic of multiple switches forms the conceptual seed of digital logic gates. And the same curiosity that motivates a student to test a circuit today is what drives an engineer to design the next generation of processors tomorrow.

In this way, the journey from balloons and batteries to diodes and LEDs becomes more than a sequence of lessons: it becomes a map of how simple physical laws transform into the astonishing sophistication of modern technology.

—

References

1. VSDIAT, VLSI System Design.

PART III — Logic

Figure 2: Exchange4Media

1 A Concise Introduction to Logic and Decision-Making

Logic is the art of reasoning clearly and systematically. It helps us make decisions that are consistent, rational, and aligned with our goals. While logic might sound abstract or complicated, it is something we use daily—even in simple choices like deciding which movie to watch. By breaking down the process into logical steps, we can see how reasoning guides us under different criteria. **Logic** is the study of valid reasoning. It asks: *Does this conclusion follow from the given information?* At its core, logic involves:

- **Premises**: The facts or assumptions we start with.
- **Reasoning**: The process of connecting those premises.
- **Conclusion**: The decision or outcome we reach.

For example:
Premise 1: I enjoy comedies.
Premise 2: This movie is a comedy.
Conclusion: I will probably enjoy this movie.

1.1 Applying Logic to Movie Decisions

When deciding on a movie, we often juggle multiple criteria. Logic helps us weigh them systematically.

1.1.1 1. Preference-Based Logic

- Premise: "I like action movies more than dramas."
- Reasoning: If two options are available, choose the action movie.
- Conclusion: Watch the action movie.

This is **deductive logic**—the conclusion follows directly from the stated preference.

1.1.2 2. Time-Based Logic

- Premise: "I only have 90 minutes free."
- Reasoning: Eliminate movies longer than 90 minutes.
- Conclusion: Choose a shorter film.

Here, logic filters options based on constraints.

1.1.3 3. Social Logic

- Premise: "My friends prefer horror movies."
- Reasoning: To enjoy together, select a horror film.
- Conclusion: Watch horror with friends.

This shows **practical logic**, balancing personal preference with group harmony.

1.1.4 4. Cost-Based Logic

- Premise: "I don't want to spend money today."
- Reasoning: Exclude paid streaming or theater options.
- Conclusion: Watch a free movie at home.

Logic here ensures decisions align with financial criteria.

1.1.5 5. Mood-Based Logic

- Premise: "I feel tired and want something light."
- Reasoning: Avoid heavy dramas or complex thrillers.
- Conclusion: Pick a comedy or animated film.

This is **contextual logic**, adapting reasoning to current emotional state.

1.2 Types of Logical Thinking

- **Deductive Logic**: From general rules to specific conclusions.

  Example: "All Marvel movies are superhero films. This is a Marvel movie. Therefore, it's a superhero film."

- **Inductive Logic**: From specific experiences to general patterns.

  Example: "The last three comedies I watched made me laugh. Comedies usually make me laugh."

- **Practical Logic**: Balancing multiple criteria to reach a workable solution.

  Example: "I like thrillers, but my friend dislikes them. Let's compromise with a mystery film."

1.3 Logic Gates in Everyday Movie Decisions

Building on the idea of using logic to choose a movie, we can now connect this to **logic gates**—the basic building blocks of digital reasoning. Logic gates take inputs (conditions) and produce outputs (decisions). Two of the most fundamental are the **OR gate** and the **AND gate**.

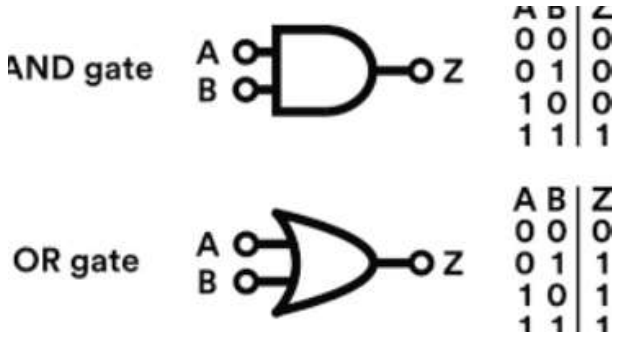

Figure 3: AND and OR Gates - ARITH-MATIC

1.3.1 OR Gate: Flexible Choice

- **Definition**: An OR gate outputs "true" if *at least one* input is true.
- **Movie Example**:
  - Condition A: "The movie is a comedy."
  - Condition B: "The movie is short (under 90 minutes)."
  - OR Gate Decision: *If either condition is satisfied, I'll watch it.*
- **Interpretation**: OR logic is inclusive—it allows multiple paths to the same decision. Even if only one preference matches, the movie qualifies.

1.3.2 AND Gate: Strict Requirement

- **Definition**: An AND gate outputs "true" only if *all* inputs are true.
- **Movie Example**:
  - Condition A: "The movie is a comedy."
  - Condition B: "The movie is short (under 90 minutes)."
  - AND Gate Decision: *I'll watch it only if it is both a comedy* ***and*** *short.*
- **Interpretation**: AND logic is restrictive—it demands that all criteria be satisfied before the decision is made.

The Styles of Expression Just as we can express our thoughts in different ways, as written, spoken, and signally expressed, they are different ways of expression digitally - topology or fallacy. For example, using binary, we can write it as 0 or 1 - that is all. Using Boolean logic, which is a system of logic based on two values, **True** (represented as 1) and **False** (represented as 0). It uses logical operators such **as AND**, **OR**, and **NOT** to manipulate these values and form the basis for digital circuits, programming, and decision-making in computing. Named after mathematician George Boole, it provides a precise way to determine the truth value of a logical expression. Similarly, it can also be reflected upon as High or Low too.

X	Y	OR (X+Y)	AND (X·Y)	NOR ($X+Y$)	NAND ($X \cdot Y$)
0	0	0	0	1	1
0	1	1	0	0	1
1	0	1	0	0	1
1	1	1	1	0	0

Figure 4: Truth Table for Various Gates

2 Truth Tables and the Universal Operator, and Theorems

Logic is the language of clarity, and at its foundation lie truth tables, the universal operator, and the theorems that bind them together. Truth tables provide the simplest yet most powerful way to visualize the outcomes of logical statements, mapping every possible input to its corresponding truth value. The universal operator, often symbolized by NAND, demonstrates how a single connective can generate the entire structure of propositional logic, revealing the elegance of reduction and completeness. From these building blocks emerge theorems—formal statements that capture the essence of logical reasoning and allow us to prove, deduce, and extend knowledge with precision. Together, these concepts form the backbone of mathematical logic, computer science, and philosophical inquiry, offering not only tools for calculation but also a framework for understanding the very structure of rational thought.

Truth tables form the foundation of modern logic analysis. As we discussed earlier. Here is a summary sheet for some common gates, often used in semiconductor design-

An OR gate is a digital logic gate that outputs a high (1) if any of its inputs are high (1). It only outputs a low (0) when all of its inputs are low (0). The Boolean expression for a two-input OR gate is Y=A+B, where the "+" sign represents the OR operation. Key characteristics include -

- **Function:** Performs a logical OR operation.
- **Output:** High (1) if input A is high, or input B is high, or both are high. Low (0) only if both A and B are low.
- **Boolean expression:** Y=A+B
- **Inputs and outputs:** Can have two or more inputs, but only one output.
- **Circuit:** Can be implemented using electronic components like diodes or transistors. A simple analogy is switches in parallel: if any switch is closed, the circuit is complete.

The AND gate is next up. An AND gate is a basic digital logic gate that produces a high output (1) only when all of its inputs are high (1). It performs a logical conjunction, meaning the output is the result of multiplying the inputs. AND gates are fundamental building blocks in digital circuits, used in applications like arithmetic operations and control systems. How it works

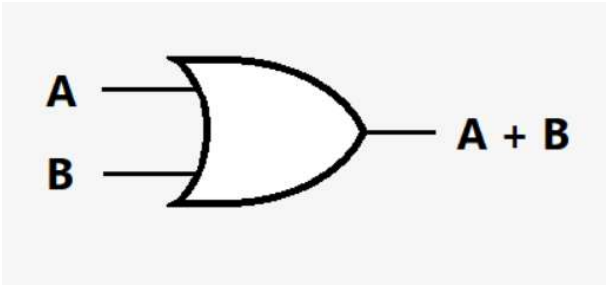

Figure 5: OR Gate - MakeCode Adafruit

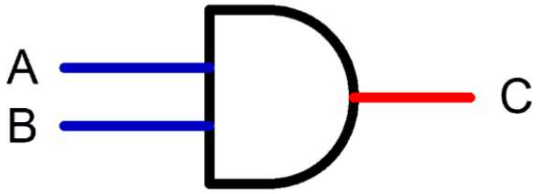

Figure 6: AND Gate - Electricaltechnology.org

- **Inputs and outputs**: An AND gate has two or more inputs and a single output. The inputs and outputs can be in one of two states: high/low or true/false.
- **Logical function**: The output is true (high) *if and only if* all of its inputs are true (high). If any input is false (low), the output will be false (low).
- **Mathematical representation**: The logical AND operation is represented by a dot or multiplication symbol. For two inputs, it is expressed as: C=A x B.
- **Truth table**: A truth table shows all possible input combinations and their corresponding outputs. For a two-input AND gate, the output is only 1 when both inputs are 1.

Applications

- Arithmetic circuits: AND gates are used in circuits that perform calculations, such as adders and multipliers.
- Control systems: They are essential for control systems that require multiple conditions to be met simultaneously. For example, a traffic light system might use an AND gate to turn the green light on only when the sensors for all roads are clear.
- Security systems: An alarm could be triggered by an AND gate that requires multiple sensors to be activated before sounding the alarm.

NOT Gate A NOT gate, also known as an inverter, is a basic logic gate that performs logical negation on a single input. It has one input and one output, and its function is to output the opposite of the input; if the input is 1 (high), the output is 0 (low), and vice versa. This behavior is represented in a truth table and can be implemented using transistors or integrated circuits (ICs) like the 7404.

Key characteristics of a NOT gate

- **Single input/output:** A NOT gate has only one input and one output terminal.
- **Logical negation:** It inverts the input signal, changing 0 to 1 and 1 to 0.

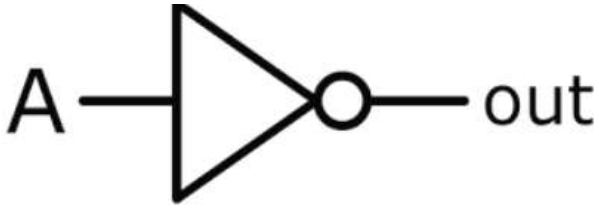

Figure 7: NOT Gate - Wikipedia

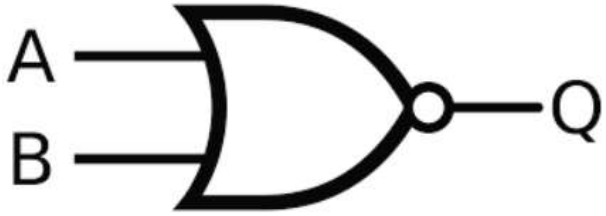

Figure 8: NOR Gate - Wikipedia

- **Symbol:** The symbol for a NOT gate is a triangle with a small circle at the output.
- **Boolean expression:** The output is represented as A bar or (NOT A)

NOR Gate A NOR gate is a digital logic gate that produces a high output (1) only when all of its inputs are low (0). It is the negation of an OR gate and is considered a **universal gate**, meaning it can be used to create any other basic logic gate (AND, OR, NOT). This makes it a fundamental building block in digital circuits for applications like memory, alarm circuits, and signal processing.

Applications

- Memory: NOR flash memory uses NOR gates in its architecture for non-volatile storage.
- SR Latch: Two NOR gates can be configured to create an SR latch, a simple form of memory that can remember its last state.
- Alarm Circuits: NOR gates are used in designing alarm or tamper circuits.
- Signal Processing: They are used in signal processing for noise reduction and filtering.
- Keyboards: They help capture keystrokes on computer keyboards and calculators.

NAND Gate A NAND gate is a digital logic gate that produces a low output (0) only when all of its inputs are high (1). It is the inverse of an AND gate, and its output is high (1) if any of its inputs are low (0). Because it can be used to create all other logic gates, the NAND gate is known as a "universal gate".

How it works

- A NAND gate is formed by combining an AND gate with a NOT gate.
- The output is determined by its inputs, often represented in a truth table.
- **Boolean expression:** Z = A x B whole bar. This can be read as "not A and B" or "A AND B, then inverted"

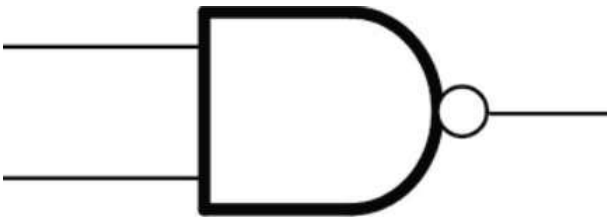

Figure 9: NAND Gate - RS Components

The Climax - Derivation of Gates and Weaving the Tapestry Till now, we've individually discussed about eahc of the logic gates central to semiconductor design, but the key point is in linking them together. When logic gates are combined, they create **logic circuits** that can perform more sophisticated tasks. The linking process involves connecting the output of one gate to the input of another, allowing signals to flow through multiple stages of decision-making.

- **Combinational Circuits**:

  These circuits depend only on current inputs. Examples include:

  - **Adders**: Built using XOR and AND gates to perform binary addition.
  - **Multiplexers**: Use combinations of AND, OR, and NOT gates to select data inputs.
  - **Encoders/Decoders**: Translate information between formats using structured gate networks.

- **Sequential Circuits**: By linking gates with feedback loops, circuits can "remember" past inputs. Examples include:

  - **Flip-Flops**: Created using NAND or NOR gates to store a single bit of data.
  - **Registers and Counters**: Built from multiple flip-flops to store and manipulate larger data sets.

2.0.1 The Power of Integration

Linking gates together transforms simple binary operations into systems capable of:

- Performing arithmetic (addition, subtraction, multiplication).
- Making logical decisions (comparisons, condition checks).
- Storing and retrieving information (memory units).
- Driving entire processors and computers.

For instance, a **half-adder** circuit combines an XOR gate (for the sum) and an AND gate (for the carry). Extending this idea, multiple adders can be linked to form an **Arithmetic Logic Unit (ALU)**, the heart of a CPU.

3 Derivation of Logic Gates by The Universal Operator

Formerly, we discussed that NAND and NOR gates are "universal operators", which means that they can be combined to create other gates, i.e. having the same boolean operation, resulting in the same result. Let us briefly survey the same now, and prior to that, let us review some important Boolean relationships corresponding to that.

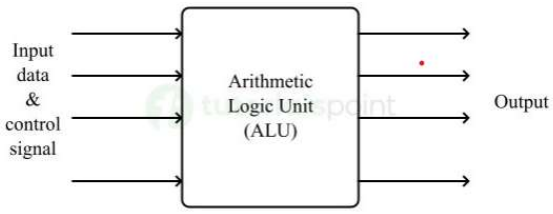

Figure 10: ALU - TutorialsPoint

4 Expanded Boolean Identities

4.1 Fundamental Identities

$A + 0 = A \qquad A \cdot 1 = A \qquad A + 1 = 1 \qquad A \cdot 0 = 0 \qquad A + A = A \qquad A \cdot A = A$

4.2 Complement Laws

$$A + \overline{A} = 1 \qquad A \cdot \overline{A} = 0$$

4.3 Commutative Laws

$$A + B = B + A \qquad A \cdot B = B \cdot A$$

4.4 Associative Laws

$$(A + B) + C = A + (B + C) \qquad (A \cdot B) \cdot C = A \cdot (B \cdot C)$$

4.5 Distributive Laws

$$A \cdot (B + C) = (A \cdot B) + (A \cdot C)$$
$$A + (B \cdot C) = (A + B) \cdot (A + C)$$

4.6 Absorption Laws

$$A + (A \cdot B) = A \qquad A \cdot (A + B) = A$$

4.7 De Morgan's Theorems

$$\overline{A \cdot B} = \overline{A} + \overline{B} \qquad \overline{A + B} = \overline{A} \cdot \overline{B}$$

4.8 Redundancy Theorem

$$A + (\overline{A} \cdot B) = A + B \qquad A \cdot (\overline{A} + B) = A \cdot B$$

4.9 Consensus Theorem

$$(A \cdot B) + (\overline{A} \cdot C) + (B \cdot C) = (A \cdot B) + (\overline{A} \cdot C)$$

X	Y	$X+Y$	$\overline{X+Y}$	$\overline{X}$	$\overline{Y}$	$\overline{X} \cdot \overline{Y}$
0	0	0	1	1	1	1
0	1	1	0	1	0	0
1	0	1	0	0	1	0
1	1	1	0	0	0	0

Figure 11: Truth Table for DeMorgan

4.10 Other Useful Simplifications

- **Double Negation:**
$$\overline{\overline{A}} = A$$
- **Duality Principle:** Every Boolean identity has a dual obtained by interchanging + and ·, and swapping 0 and 1.

Now that we are empowered with these, we can even test them out using truth tables. For now, we will consider moving on to the derivation. We know that two Boolean operations are equal if their outputs are same for a particular set of input values. We see that these two produce the same values for particular input values. We can draw out a truth table for that too.

5 Deriving the NOT Gate using NAND Gate

Let's start with the simplest case. Consider a NAND gate with both inputs equal to x. The Boolean expression for the output of a NAND gate is:

$$\overline{x \cdot x} = \overline{x}$$

Since $x \cdot x = x$ (this is the property of the AND gate), the output of the NAND gate is simply the negation of x, which is equivalent to a NOT gate. Thus, a single NAND gate with both inputs set to x acts as a NOT gate.

$$\text{NAND}(x, x) = \overline{x} = \text{NOT}(x)$$

6 Deriving the AND Gate using NAND Gates

Now, let's derive the AND gate using NAND gates. The AND gate can be constructed by applying the following steps:

1. First, consider the NAND gate with inputs x and y. The output of this gate will be:

$$\overline{x \cdot y}$$

2. Next, to invert this output (i.e., to get $x \cdot y$, the output of an AND gate), we apply another NAND gate to the output of the first NAND gate. Let's label the first NAND gate output as $A = \overline{x \cdot y}$.

$$\text{NAND}(A, A) = \overline{A \cdot A} = \overline{\overline{x \cdot y} \cdot \overline{x \cdot y}} = x \cdot y$$

Thus, using two NAND gates, we have effectively created an AND gate.

7 Deriving the OR Gate using NAND Gates

To derive the OR gate from NAND gates, we can apply DeMorgan's Law. DeMorgan's Law states that:

$$x + y = \overline{\overline{x} \cdot \overline{y}}$$

We can implement the right-hand side using NAND gates. To do this:

1. First, use two NAND gates to create the NOT operation for x and y. Each input is passed through a NAND gate with both inputs set to x and y respectively, as shown:

$$\overline{x} = \text{NAND}(x, x), \quad \overline{y} = \text{NAND}(y, y)$$

2. Then, take the outputs of these two NAND gates and input them into a third NAND gate. This will give us the OR operation:

$$x + y = \text{NAND}(\overline{x}, \overline{y}) = \overline{\overline{x} \cdot \overline{y}}$$

Thus, by using three NAND gates, we can create an OR gate.

8 Constructing the AND Gate Using NOR Gates

To construct an AND gate using only NOR gates, we will first recall the Boolean expression for an AND gate:

$$x \cdot y$$

A NOR gate produces the negation of the OR operation. The Boolean expression for a NOR gate is:

$$\text{NOR}(x, y) = \overline{x + y}$$

Now, to construct an AND gate using only NOR gates, we can proceed as follows:

1. First, we need to create a NOT operation using NOR gates. A NOR gate with both inputs being the same value (i.e., x) will give us a NOT gate:

$$\text{NOR}(x, x) = \overline{x}$$

2. Then, we can use two NOR gates to implement the AND operation. The first NOR gate gives the negation of x and y, and the second NOR gate will give us the negation of the negation, effectively performing the AND operation:

$$\text{AND}(x, y) = \overline{\overline{x} + \overline{y}}$$

Thus, using NOR gates, the AND gate can be constructed as follows:

$$x \cdot y = \overline{\overline{x} + \overline{y}}$$

This requires two NOR gates: one to negate x and y individually, and another to negate the result of the OR operation.

9 Constructing the OR Gate Using NOR Gates

Next, let's construct an OR gate using only NOR gates. The OR gate has the following Boolean expression:

$$x + y$$

We will again use the property of the NOR gate. We know that the NOR gate is the negation of the OR operation:

$$\text{NOR}(x, y) = \overline{x + y}$$

To construct an OR gate using NOR gates, we can use the following approach:

1. First, we create the negation of x and y by using NOR gates:

$$\overline{x} = \text{NOR}(x, x), \quad \overline{y} = \text{NOR}(y, y)$$

2. Then, we apply NOR to these negated inputs:

$$x + y = \overline{\overline{x} \cdot \overline{y}}$$

Thus, using NOR gates, we can construct the OR gate as:

$$x + y = \overline{\overline{x} \cdot \overline{y}}$$

This requires two NOR gates for negating the inputs and a third NOR gate to perform the OR operation.

10 Curiosity, Conclusions and Connections - From Foundations to Fascinations

The study of logic, automation, and semiconductor gates forms the cornerstone of modern computing. These concepts, though seemingly abstract at first glance, are the very foundations upon which semiconductor design and advanced processor architectures such as RISC-V are built. By exploring truth tables and the fundamental logic gates—AND, OR, NOR, NOT, and NAND—we begin to uncover the elegant simplicity that drives the complexity of digital systems.

Logic gates are the basic units of decision-making in electronics. Each gate performs a specific operation on binary inputs, producing outputs that can be predicted and represented through truth tables. This predictability is not trivial; it is the essence of automation. When millions, or even billions, of these gates are combined, they enable machines to execute instructions with precision and reliability. The deterministic nature of logic ensures that every computation, from the simplest addition to the most complex algorithm, is grounded in a framework of consistency.

The importance of these gates extends far beyond their individual functions. Their true power lies in **composability**. By linking gates together, engineers construct circuits capable of performing arithmetic, storing memory, and controlling processes. This scalability allows the same principles to apply across devices of vastly different complexity—from microcontrollers embedded in household appliances to high-performance CPUs powering artificial intelligence.

Moreover, the study of logic gates provides a gateway to understanding processor architectures such as RISC-V. At its core, RISC-V is an open-source instruction set architecture that thrives on modularity and efficiency. Yet beneath its sophisticated design lies the same fundamental logic operations we first encounter in truth tables. The arithmetic logic unit (ALU),

References

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